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13. ABSTRACT (Maximum 200 words) The main thrust of this project is experiments to manipulate metastable He atoms with polychromatic optical forces, and to study their properties in dark states, entangled states, and other superpositions. Several Doctoral theses were completed and defended, and several papers were published.			
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Enclosure 1

Final Report on Grant number 41369-PH (local # 011963)

This one-year grant terminated on 30 August, 2002, after an additional one-year, no-cost extension. It was a terminal continuation of grant # 36413-PH, and therefore this report contains much of the information that was in the final report of that one. However, discussion of the accomplishments that were completed before the start of this grant have been left out. Also, the publications and abstracts have been brought up to date, and there has been considerable new progress in the helium experiments.

A. Velocity Selective Resonances and Dark States

We have discovered a new kind of dark state, related to VSCPT, but for atoms moving at relatively high speeds in applied dc magnetic fields. The velocity-selective resonances (vsr) discovered several years ago are produced by laser cooling in a magnetic field B , and are centered at a velocity $v_{vsr} = \mu_B g B / \hbar k = \omega_Z / k$ instead of $v = 0$ [1]. Here ω_Z is the Zeeman shift of each internal level. These vsr left two tantalizing questions concerning 1) the origin of the force that produced them and 2) the limit of the cooling from this force [2]. Our recent measurements show that this limit is below the recoil energy, and numerical calculations confirm the result [3]. Such narrow widths cannot derive from optical damping forces [4] and therefore must arise another way. We attribute them to a family of quasi-dark states that are related to VSCPT states [5].

The key to the narrow widths arises from the ground state coherence produced by stimulated Raman transitions that connect two momentum states. Since the eigenstates of the system are the symmetric and anti-symmetric superpositions of the coupled momentum states, then as described in Ref's. [4, 6], one of these is a dark state. If the connected states are also degenerate, then the dark state formed by their superposition is stationary, and atoms that fall into it stay trapped there. The key point is that the energies must include the kinetic energy as well as the Zeeman energy. Thus degeneracy for two states $|1\rangle$ and $|2\rangle$ can mean $Mv_1^2/2 + g\mu_B B = Mv_2^2/2 - g\mu_B B$ or $\bar{v} = v_{CM} = \omega_Z/k$. Thus an applied \vec{B} -field should shift a VSCPT signal in momentum space, and this has been well established [5].

What has been missing in the picture connecting vsr and VSCPT has been the understanding that there are two independent time scales associated with the creation of the superposition of ground momentum states. One is the optical pumping time for the strongly-coupled superposition state to be emptied and the other is the leakage time out of the weakly-coupled state that would be dark and trapped in the ideal case, such as that of Ref. [7]. These notions have only recently been exposed in the 2000 thesis of Liang Liu [5] that was built on the previous work of Mary-Jo Bellanca [3]. They are now understood and have been rather thoroughly described in Ref. [2].

B. Stimulated Optical Compton Scattering (SOCS)

We have extended some earlier work on velocimetry of a laser cooled vapor [8] by implementing SOCS on the much sparser sample of atoms in an atomic beam. Usually transverse velocimetry is done by measuring the spatial distribution of the atoms at the end of the beam line, so good velocity resolution requires a long beam line and narrow beam-defining slits. By contrast, SOCS replaces this cumbersome scheme by direct velocimetry, thereby reducing the length of the atomic beam apparatus, eliminating the instrumental broadening caused by the longitudinal velocity spread, and removing the need for narrow slits that are required to maintain the spatial resolution [9]. Furthermore, a small extension of SOCS allows measurement of velocity components in two or three dimensions.

The basic principle underlying SOCS is identical to that of the Compton effect. For stimulated processes, where light is transferred from one laser beam to another, there is only the atomic motion, including its recoil, as the unconstrained experimental variable. Measuring absorption or gain allows determination of the initial atomic velocity to accuracy on the order of $v_r \equiv \hbar k/M$. The symmetry of the transition is broken through a non-uniform population of atomic momentum states. Therefore the intensity dependence of either beam on the detuning between them maps out the atomic velocity distribution on a sub-recoil scale. This work constitutes the Ph.D. thesis of Felix Chi that was defended on 11 April, 2001 (Felix is the first black Ph.D. from my lab). Our paper on this subject has now been published in Phys. Rev. A [9].

C. Beam Slowing of He* with the Bichromatic Force

In 2001 we published a paper describing observation of the bichromatic force on He* using our cryogenic atomic beam source and optical fiber amplifiers to produce the required high power light [10]. These experiments are intended to improve He* trapping capabilities because the slowing length L is more than 3.5 m [4] for a discharge source of typical kinetic temperature $T = 600$ K using the radiative force whose maximum value is F_{rad} . Even for a LN₂-cooled source whose characteristic kinetic temperature is $T \sim 150$ K, L is nearly 1 m. But the bichromatic force can slow such 1000 m/s atoms in a distance less than 1 cm, and thus there can be much smaller loss of atoms from angular dispersion and diffusive heating.

We implemented the bichromatic force on He* by driving the $2^3S_1 \rightarrow 2^3P_2$ transition at $\lambda = 1083$ nm using amplified light that originates from an external cavity-stabilized SDL-6702-H1 diode laser. The the diode laser frequency was locked to atomic resonance by saturated absorption spectroscopy. The light double-passed a 75 MHz AOM that was operated at 50% efficiency to make four frequencies [11, 12]. One of the two emerging beams had frequency components shifted by $\pm\delta \sim \pm 75$ MHz $\sim \pm 45$ γ . This beam was injected into a diode-pumped fiber amplifier to produce several hundred mW of bichromatic light. The counterpropagating laser beams crossed the atomic beam perpendicularly.

We then performed preliminary deceleration experiments using the bichromatic force at a small angle to the atomic velocities. With the AOM's we had at that time, we could expect only a small deceleration of ~ 100 m/s. We used two diode laser/AOM combinations to make a total of four frequencies in the lab frame that became two frequencies detuned from resonance by $\pm\delta = \pm 75$ MHz when Doppler shifted into the atomic rest frame at $v \sim 950$ m/s [11, 12]. The velocity range that can be covered by this value of δ is $\Delta v = 4\delta/3k \sim 110$ m/s. These beams were injected into two fiber amplifiers whose output beams were aligned to produce a force at a small angle (3°) to the velocities of the He* atoms. Since the atoms pass through the laser beam at such a small angle, it was not expanded because the interaction length in the 1.5 mm beam waist was 20 mm, consistent with achieving $\Delta v \sim 110$ m/s with $F \approx 11F_{rad}$.

We used a time-of-flight (TOF) detector apparatus that was described in previous reports to observe such decelerations. The slowed atoms appeared on the TOF signal as a shoulder delayed by ~ 75 μ s. As a check on this, we also changed the relative phase of the bichromatic fields and observed acceleration of the atoms by the same amount. Because the deceleration is at an angle to the atomic beam axis, we expect the slowed atoms to also be deflected out of the beam. With the imaging detector we were able to observe atoms deflected by ~ 2.5 mm out of the main beam over their 50 cm flight path (also corresponding to a longitudinal velocity change of ~ 100 m/s).

More recently we obtained higher frequency AOM's (400 MHz) and used these in a similar TOF experiment, and as before, we transformed the TOF signal to extract the atomic velocity distribution. We also made several changes to the geometry and alignment characteristics to have better control of the angles and beam positions. The dramatic results in Fig. 1 show He* atoms slowed up to ~ 275 m/s and cooled by a factor of ~ 20 . All atoms with velocities between 975 and 725 m/s have been swept into a narrow peak centered at 700 m/s (curve B). They appear as a peak in the velocity distribution almost completely outside the residual velocity distribution of unslowed atoms.

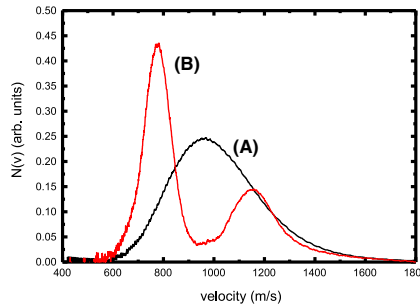


FIG. 1: The measurable force is limited by the geometry of this experiment to be $\sim 10F_{rad}$, but we believe it to be closer to $\sim 50F_{rad}$. Curve A shows the velocity distribution measured by transforming the TOF signal directly from the source. Curve B shows the distribution with a bichromatic cooling force whose parameters correspond to $\Delta v \sim 300$ m/s. The slow atoms appear as a peak in the velocity distribution almost completely outside the residual velocity distribution of unslowed atoms.

D. Optical Forces in Frequency-Modulated Light

As part of our ongoing exploration of optical forces in non-monochromatic light [10–12], we have found a new implementation of a rectified dipole force that is not limited to F_{rad} and whose damping capability extends over a somewhat larger velocity range [13]. This new kind of rectified force differs from many other previously published descriptions in fundamental ways. We use light tuned well away from resonance, with weak frequency modulation chosen to put one of the sidebands close to resonance. (We ignore the second sideband because it's weak and very far from resonance.)

This modulated beam is retroreflected to form standing waves, so we consider a two-level atom in two optical standing waves of different frequencies. The “carrier” frequency produces a strong light shift and dipole force, while the weak “sideband” causes optical pumping between the dressed states of a two-level atom that have opposite light shifts. The relative spatial phase of the two standing waves is chosen so that atoms climb (descend) potential hills shifts more often than they descend (climb). We have used it for both deflection and cooling of our He^* atomic beam. Figure 2 shows the deflected beam from the new rectified dipole force. Although it resembles Fig. 3 of Ref. [10], it is genuinely different in origin.

We have developed an intuitive model of the origin of this large force that agrees qualitatively with our measurements, and a numerical model based on an approximation to the doubly dressed states that agrees quantitatively. Although this approximate model is based on the stationary solutions of the atom+laser Hamiltonian, comparison with our measurements shows quite excellent quantitative agreement. This has now been published in Phys. Rev. A [13]. In collaboration with Leonid Yatsenko from the Ukraine Academy of Sciences, we are working on a more formal theory of atoms moving in a frequency-modulated field.

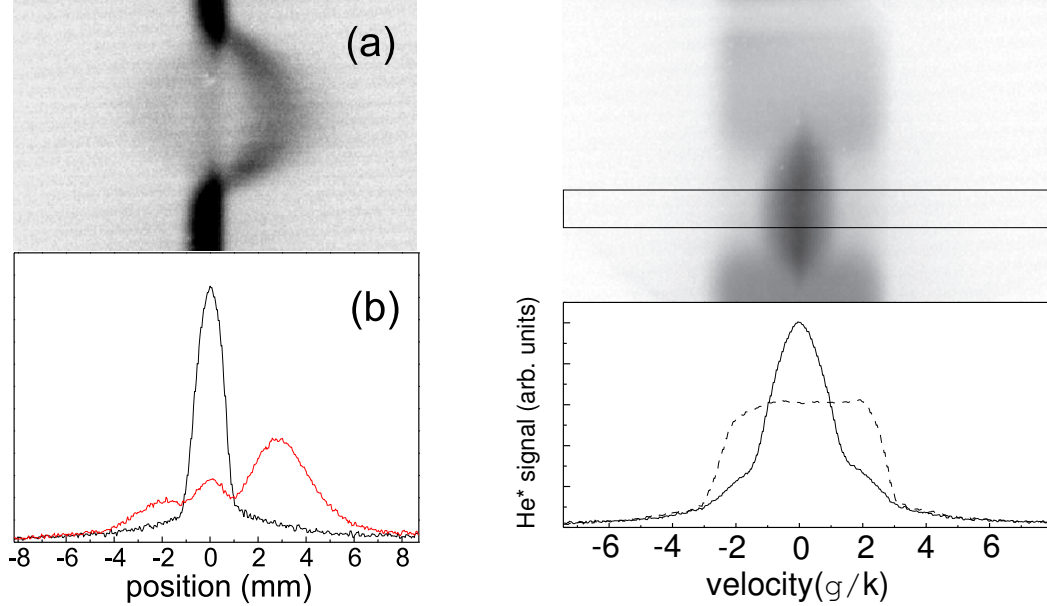


FIG. 2: The left side shows the deflected beam from the new rectified dipole force. The laser parameters are detuning = 36.2γ and -2.5γ and Rabi frequency = 23γ and 3γ for the carrier and sideband respectively. The small undeflected peak in the center arises from light emanating from the source discharge, and not atoms that failed to see the light. The smaller peak to the left is caused by atoms whose initial velocity was too high to the left to be captured by the force. The right side shows the new kind of Sisyphus cooling that derives from choosing the relative phase of the standing wave to be π . Atoms above and below the laser beam are not deflected (top and bottom of image) and so serve as indicators of the unperturbed beam profile.

E. Demonstration of Adiabatic Rapid Passage

Although bichromatic light, with its appealing π -pulse model of coherent transfer of atoms between ground and excited states is quite attractive, it is not the only way to accomplish the transfer. Adiabatic rapid passage (ARP) produced by light whose frequency is swept through resonance, is a very robust way to invert the population of two-level atoms. By the right choice of relative sweep phase in counterpropagating beams, ARP can also cause coherent exchange of momentum between atoms and field, and thus can produce a force that is very much larger than F_{rad} [14]. To test this, we have used an EOM to sweep the frequency of our light beams through resonance, and have indeed observed forces that are many times larger than F_{rad} [15]. We now have more degrees of freedom (sweep rate, sweep range, center frequency, Rabi frequency, relative phase, etc.) and varying these has led to some unexpected laser cooling effects as well. Even when these experiments were somewhat preliminary, we were invited to submit a paper to the British Journal of Optics B, Quantum and Semiclassical Optics, and it has now been published [16].

F. Educating Our Students

Our Ph.D. program has led its alumni into excellent starts on careers as professional physicists. In addition, we have provided research opportunities for numerous Masters students, undergraduates, and high school students. These students take part in the daily life of our active research group, and thereby learn how things really work. All of our students enjoy our broad weekly seminar in atomic physics in many of which they give talks about their own work thus providing experience in presenting talks. The textbook written in collaboration with former post-doc Peter van der Straten has received many excellent reviews both in the US [17] and internationally, and has been widely complimented in private communications.

1. Graduate Students: During the past two years, three students have completed their Ph.D. theses. They have all found excellent positions in industry or academia, and are continuing their careers as profesional physicists. Their present positions and their dates of Ph.D completion are in a chart below. Further information about their work can be found in the several publications that result therefrom. The details of their work are available in their theses.

2. Laser Teaching Center: In the summer of 1999 our department opened a new facility built completely from industrial and private funds (the PI is its founder and director). It has a suite of four well-equipped and furnished laboratories totaling over 120 m². The PI has also obtained University support for its operation with a full-time, Ph.D. instructor and \$30k/yr for supplies and equipment.

Many of its high school alumni (even from years past) are now in college, and many of them have won Westinghouse/Intel finalist or semifinalist prizes in the past years. Often these younger students work along with our graduate students on their various projects. Many of our undergraduates have gone off to graduate school or industrial jobs with considerable experience in a research environment. Our undergraduates are brought to us via the University's URECA program, and NSF's REU and RAIRE programs (Stony Brook is one of 10 NSF RAIRE institutions and the PI is an active participant).

Information about this very exciting and innovative facility at Stony Brook can be found at <http://laser.physics.sunysb.edu/>. The tables of student projects on that site, too large to reproduce here, give some flavor of the variety and depth of the superb work done by these younger students in the recent years.

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2. “Precision Velocimetry in a Thermal Atomic Beam by Stimulated Optical Compton Scattering” (with F. Chi and M. Partlow), Phys. Rev. **A64**, 043407, (2001).
3. “Strong Optical Forces in Frequency Modulated Light”, (with M. Cashen, O. Rivoire, V. Romanenko, and L. Yatsenko), Phys. Rev. **A64**, 063411 (2001).
4. “Coherent Exchange of Momentum Between Atoms and Light” (with M. Cashen, O. Rivoire, and L. Yatsenko), J. Opt. B: Quantum & Semiclass., **4**, 75, (2002).
5. “Evolution of Coherent Dark States” (with L. Liu, and M. J. Bellanca), Phys. Rev. **A65**, 043401 (2002).
6. “Atomic Nanofabrication: Atomic Deposition and Lithography by Laser and Magnetic Forces”, (with D. Meschede) J. Phys. D, **36**, R17, (2003)
7. “Laser Cooling and Trapping of Atoms”, (with P. van der Straten), accepted by J. Opt. Soc. Am. B for special issue on laser cooling to be published in May, 2003 (invited).
8. “Optical Forces on Atoms in Non-Monochromatic Light”, (with M. Cashen), accepted by J. Opt. Soc. Am. B for special issue on laser cooling to be published in May, 2003.

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2. “Velocity Selective Raman Resonances at High Recoil”, (with O. Kritisun and C. Affolderbach) Bull. Am. Phys. Soc. **46**, No. 3, 99 (2001) S5-20.
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8. “Slowing Metastable Helium (He*) Using the Bichromatic Force”, (with M. Cashen and M. Partlow), Bull. Am. Phys. Soc. **47**, No. 3, 102 (2002), P6 22.
9. “Producing Rydberg States of Helium Using STIRAP”, (with O. Kritisun and B. Dietzik), Bull. Am. Phys. Soc. **47**, No. 3, 109 (2002), P6 66.
10. “Short Distance Slowing of a He Atomic Beam”, (with M. Cashen and M. Partlow), ICAP XVIII, Cambridge, MA, 175, (2002), F24.

PROJECT PERSONNEL

Research Professor

Prof. Thomas Bergeman

Former Ph.D. Students

Name	Degree Date	Present Occupation
Felix Chi	April 2001	Corvis Corp.
Jeff Hack	Dec 2001	Southern Co.
Matt Cashen	May 2002	Stanford University

Present Ph.D. Students

Name	Thesis Project
Matt Partlow	Bichromatic Force Collimation of Helium Beam
Oleg Kritsun	STIRAP Excitation of Rydberg States of Helium
Xiyue Miao	Bichromatic Force Collimation of Helium Beam
Seung Hyun Lee	Production of Rydberg states of Helium
Matt Eardley	Production of Rydberg states of Helium

Visiting Students

Name	Home Institution	Duration	Date
Christoph Affolderbach	Inst. Angewandte Physik, Bonn	5 months	2000-2001
Olivier Rivoire	École Normale Supérieure, Paris	6 months	2001

Senior Visitors

Name	Home Institution	Duration	Date
Dr. Robert Wynands	Inst. Angewandte Physik, Bonn	4 weeks	2000
Dr. Leonid Yatsenko	Ukrainian Academy of Sciences	8 weeks total, multiple visits	2000-2002
Prof. Dieter Meschede	Inst. Angewandte Physik, Bonn	4 weeks	2002